

Update on $\pi^0 \rightarrow e^+e^-e^+e^-$ and $\pi^0 \rightarrow e^+e^-e^+e^-\gamma$

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KTeV Collaboration Meeting
February 14, 2004

Outline

- $\pi^0 \rightarrow e^+ e^- e^+ e^-$ Branching Ratio:
 - Preliminary Result
 - Systematic Uncertainties
- $\pi^0 \rightarrow e^+ e^- e^+ e^-$ Form Factor:
 - Likelihood Method
 - Results and Systematic Studies
- $\pi^0 \rightarrow e^+ e^- e^+ e^- \gamma$ Branching Ratio:
 - Background
 - Result

$\pi^0 \rightarrow 4e$ BR: Method

Signal Mode (DD):

$$K_L \rightarrow \begin{cases} \pi^0 \rightarrow e^+ e^- e^+ e^- \\ \pi^0 \rightarrow \gamma\gamma \\ \pi^0 \rightarrow \gamma\gamma \end{cases}$$

Normal Mode (2D):

$$K_L \rightarrow \begin{cases} \pi^0 \rightarrow e^+ e^- \gamma \\ \pi^0 \rightarrow e^+ e^- \gamma \\ \pi^0 \rightarrow \gamma\gamma \end{cases}$$

$$R = \frac{N_{DD}^{\text{obs}}}{N_{2D}^{\text{obs}}} \frac{\epsilon_{2D}}{\epsilon_{DD}} = \frac{B(\pi^0 \rightarrow e^+ e^- e^+ e^-) \cdot B(\pi^0 \rightarrow \gamma\gamma)}{B^2(\pi^0 \rightarrow e^+ e^- \gamma)}$$

⋮
⋮

$\pi^0 \rightarrow 4e$ BR: External Conversion

Single Conv (1C):

$$K_L \rightarrow \begin{cases} \pi^0 \rightarrow e^+ e^- \gamma \\ \pi^0 \rightarrow \gamma \gamma \\ \pi^0 \rightarrow \gamma \gamma \end{cases}$$

+ 1 conversion

Double Conv (2C):

$$K_L \rightarrow \begin{cases} \pi^0 \rightarrow \gamma \gamma \\ \pi^0 \rightarrow \gamma \gamma \\ \pi^0 \rightarrow \gamma \gamma \end{cases}$$

+ 2 conversions

$$P(2D) = 9.0 \times 10^{-5}$$

$$P(1C) = 8.9 \times 10^{-5}$$

$$P(DD) = 1.9 \times 10^{-5}$$

$$P(2C) = 3.5 \times 10^{-5}$$

$\pi^0 \rightarrow 4e$ BR: Analysis Overview

- Good 4–Track Vertex
- 8 Hardware Clusters
- Well Separated Tracks
- Consistent with DD or 2D:

$$\chi_{DD}^2 = \left(\frac{M_{4e} - M}{\sigma_{4e}} \right)^2 + \left(\frac{M_{\gamma\gamma 1} - M}{\sigma_{\gamma\gamma}} \right)^2 + \left(\frac{M_{\gamma\gamma 2} - M}{\sigma_{\gamma\gamma}} \right)^2$$

$$\chi_{2D}^2 = \left(\frac{M_{ee\gamma 1} - M}{\sigma_{ee\gamma}} \right)^2 + \left(\frac{M_{ee\gamma 2} - M}{\sigma_{ee\gamma}} \right)^2 + \left(\frac{M_{\gamma\gamma} - M}{\sigma_{\gamma\gamma}} \right)^2$$

$\pi^0 \rightarrow 4e$ BR: Cuts

Quantity	Requirement
Cluster Energy	$> 2 \text{ GeV}$
Total Energy	$40 - 210 \text{ GeV}$
Cluster Separation	$> 5 \text{ cm}$
Track Momentum	$> 2 \text{ GeV}$
E/p	$0.93 - 1.07$
Track Separation	$> 2 \text{ mm}$
Vertex χ^2	< 40
Offmag χ^2	< 100
Vertex Z	$94 - 157 \text{ m}$
Event χ^2	< 12
Total Mass	$480 - 515 \text{ MeV}$
P_t^2	$< 0.0008 \text{ GeV}^2$

$\pi^0 \rightarrow 4e$ BR: BG Subtraction

Dataset	97		99	
Mode	DD	2D	DD	2D
Candidates	10738	53667	17923	81990
1C	177	1050	367	2027
2C	5	52	18	108
XO	50	119	90	215
Total BG	232	1221	475	2350
Signal	10506	52446	17448	79640

$\pi^0 \rightarrow 4e$ BR : Results

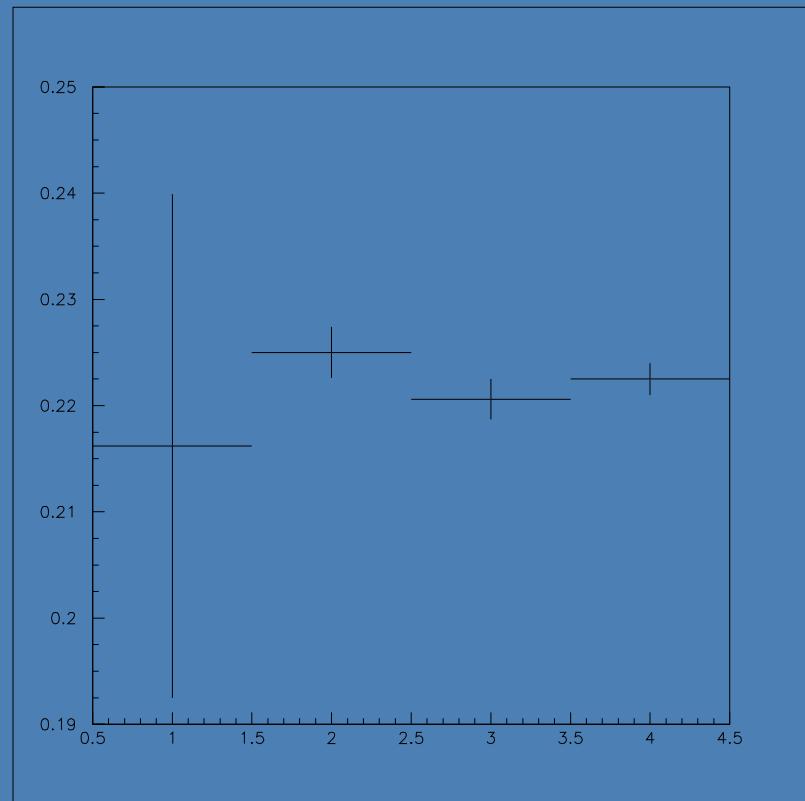
$$R_{PDG} = 0.2162 \pm 0.0237$$

$$R_{97} = 0.2250 \pm 0.0024$$

$$R_{99} = 0.2206 \pm 0.0019$$

$$R_{All} = 0.2225 \pm 0.0015$$

(My errors are statistical)



$\pi^0 \rightarrow 4e$ BR: Systematic Studies

Category	Source	Error (%)
Theory:	$4e(\gamma)$	1.70
	$f(x_1, x_2)$?
Acceptance:	Cut Var	1.20
	DC Res	0.84
	Material	0.16
	BG's	0.09
	DC Ineff	0.04
	Csl Res	0.02
MC Stat:		0.39
Total Int:		2.29
External:	$B(\pi^0 \rightarrow e^+ e^- \gamma)$	5.44
Total:		5.90

$\pi^0 \rightarrow 4e$ BR: Remaining Issues

- Two systematics to finish:
 - Second order radiative corrections
 - Uncertainties in the form factor
- Revisit cut variation study

$\pi^0 \rightarrow 4e$ FF: Form Factor

$$C_{\mu\nu\rho\sigma} \sim f(x_1, x_2; \alpha) [\epsilon_{\mu\nu\rho\sigma} + (\kappa + i\eta)(g_{\mu\rho}g_{\nu\sigma} - g_{\mu\sigma}g_{\nu\rho})]$$

$$f(x_1, x_2; \alpha) = 1 + \alpha \left(\frac{x_1}{x_1 - M_\rho^2/M^2} + \frac{x_2}{x_2 - M_\rho^2/M^2} \right)$$

$$+ \beta \frac{x_1 x_2}{(x_1 - M_\rho^2/M^2)(x_2 - M_\rho^2/M^2)}$$

$$\beta = -(1 + 2\alpha)$$

$\pi^0 \rightarrow 4e$ FF: Likelihood Fit

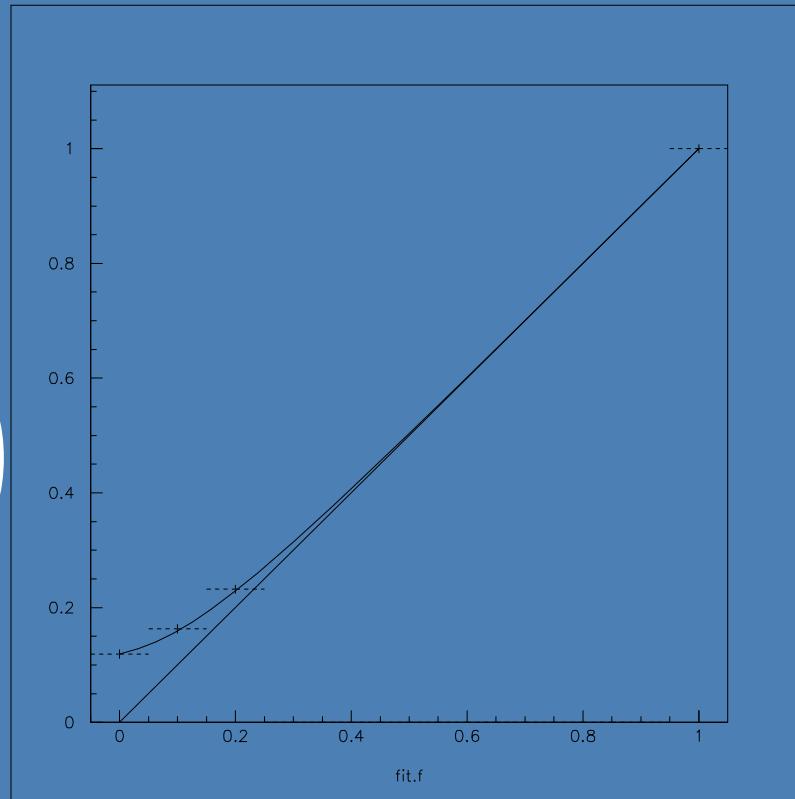
- κ and η are expected to be zero for CP conserving decays
- Extract α , κ , and η using a 3-D unbinned likelihood fit
- The raw value of η is biased due to the resolution on the angle ϕ between the ee pairs

$\pi^0 \rightarrow 4e$ FF: Resolution Bias

MC samples generated with η yield η' :

$$\eta' = \eta + b \left(\frac{e^{-m\eta} - e^{-m}}{1 - e^{-m}} \right)$$

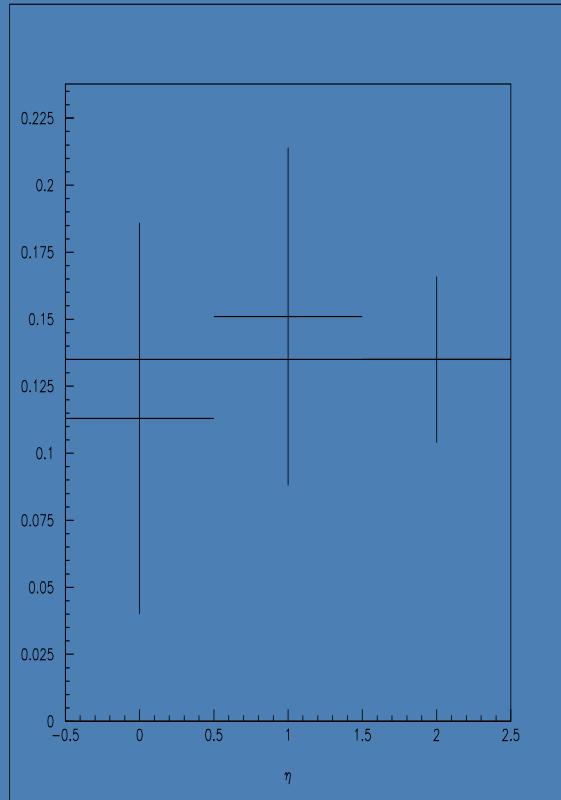
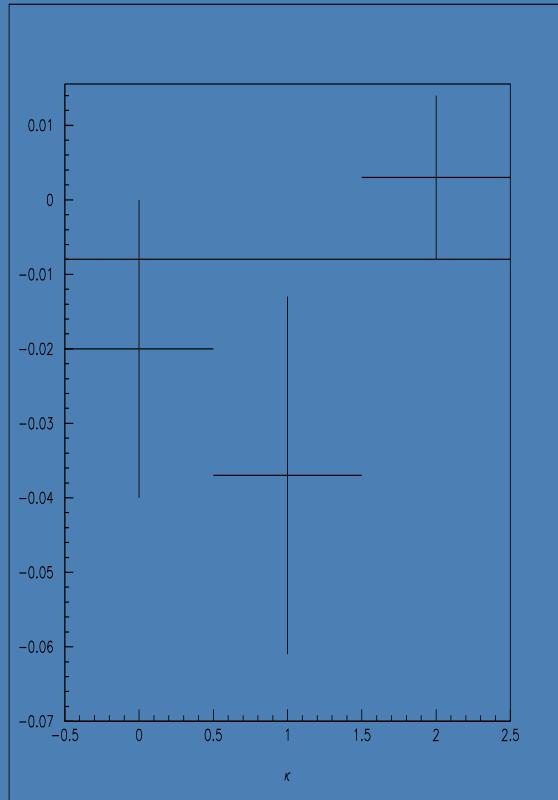
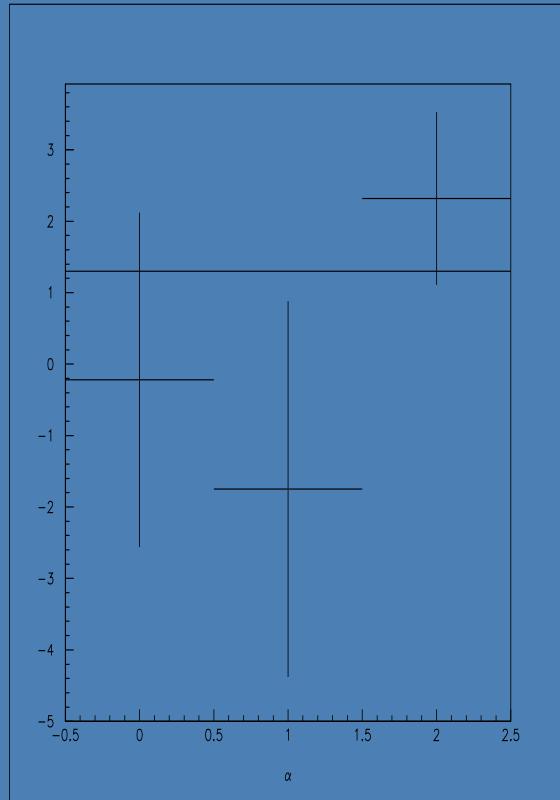
$b = 0.12$ and $m = 7.0$



$\pi^0 \rightarrow 4e$ FF: Results

Dataset	α	κ	η
Win97	-0.2 ± 2.3	-0.020 ± 0.020	0.113 ± 0.073
Sum97	-1.8 ± 2.6	-0.034 ± 0.024	0.151 ± 0.063
99	$+2.3 \pm 1.2$	-0.003 ± 0.011	0.135 ± 0.031
Combo	$+1.3 \pm 1.0$	-0.008 ± 0.009	0.135 ± 0.026
χ^2/dof	1.2	1.4	0.1

$\pi^0 \rightarrow 4e$ FF: Comparison

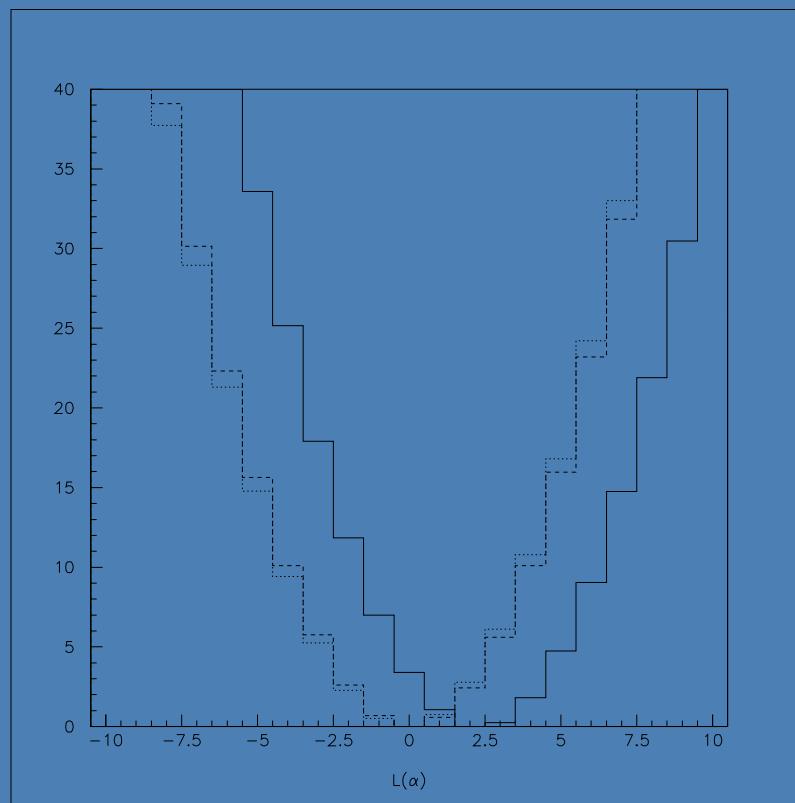


$\pi^0 \rightarrow 4e$ FF: Systematic Errors

Source	α	κ	η
Normalization	0.22	0.0028	0.0045
Rad Corr	0.14	0.0001	0.0010
Cut Variation			
Material			
Total Systematic	0.26	0.0028	0.0046

$\pi^0 \rightarrow 4e$ FF: Radiative Effects

The error due to neglecting second order radiative corrections is estimated by fitting with a normalization which is shifted with respect to the nominal normalization by the square of the difference between the tree-level and the first order correction.



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$\pi^0 \rightarrow 4e$ FF: Remaining Issues

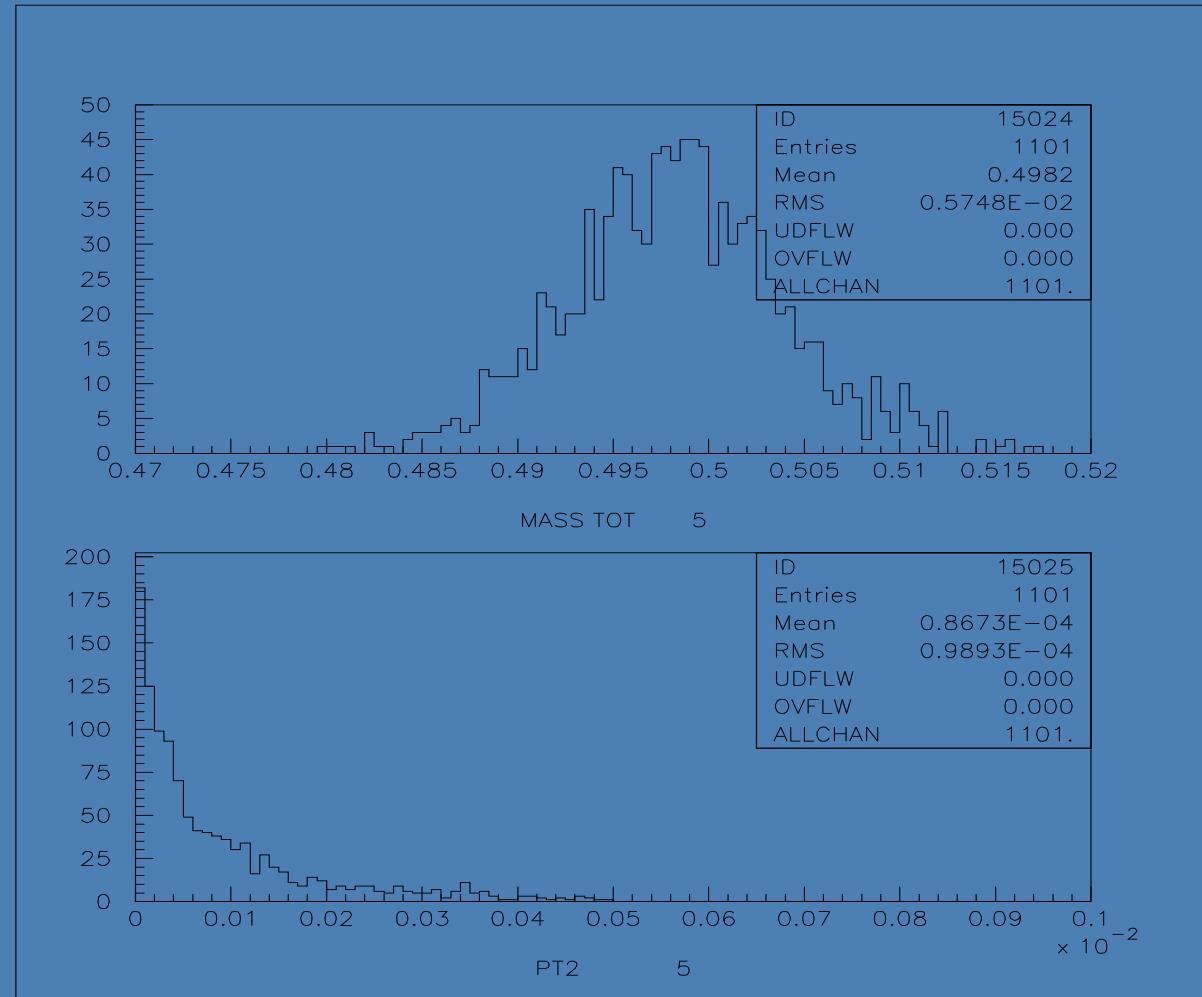
- Finish cut variation study
- Study resolution dependence

$\pi^0 \rightarrow 4e\gamma$ BR: Overview

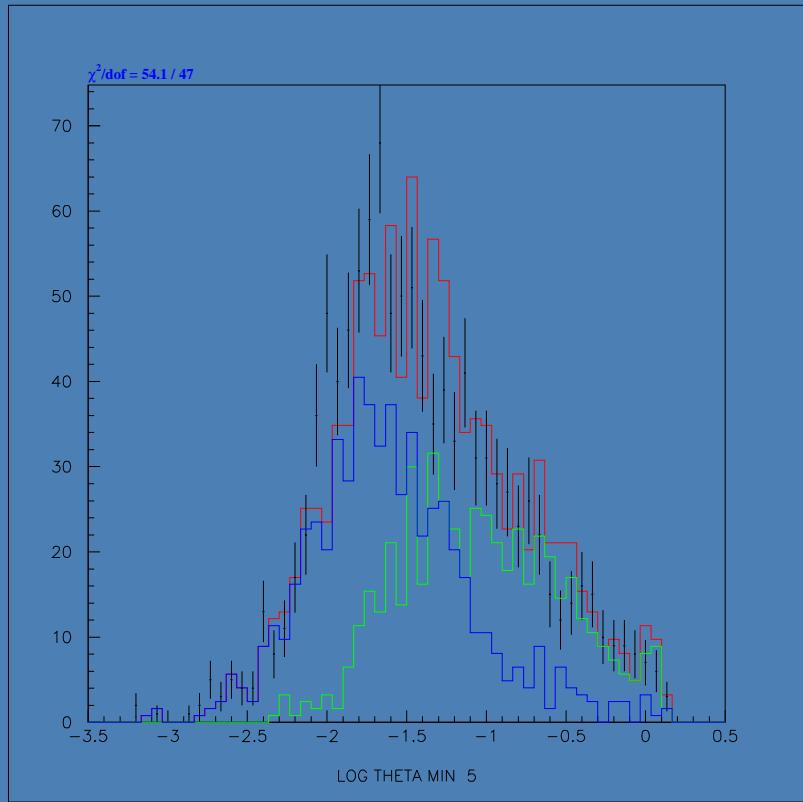
- 4–Track events with 9 clusters
- Backgrounds include:
 - Conversions
 - Double–Single Dalitz with radiation
 - Double Dalitz with external radiation
- Cuts are similar to $\pi^0 \rightarrow 4e$ analysis with one addition: a cut on the smallest angle between the photon and any electron (θ_{\min})
- Branching ratio is defined for events with $x_{4e} < 0.90$

$\pi^0 \rightarrow 4e\gamma$ BR: Signal

97 | 99
354 | 747



$\pi^0 \rightarrow 4e\gamma$ BR: Results



$$N_{x<} = \frac{\epsilon_{x>}^{\theta<} N_{\theta>} - \epsilon_{x>}^{\theta>} N_{\theta<}}{\epsilon_{x<}^{\theta>} \epsilon_{x>}^{\theta<} - \epsilon_{x<}^{\theta<} \epsilon_{x>}^{\theta>}}$$

For $\theta_{\min} = 46$ mrad:

$$N_{\theta>} = 436 \quad N_{\theta<} = 665$$

$$B(\pi^0 \rightarrow 4e\gamma, x < 0.9) = (1.25 \pm 0.06) \times 10^{-6}$$

⋮
⋮

$\pi^0 \rightarrow 4e\gamma$ BR: Remaining Issues

- Estimate residual conversion background
- Optimize θ_{\min} cut
- Repeat $\pi^0 \rightarrow 4e$ systematics

Time Line

- Wrap up remaining issues (2–3 weeks)
- Defend in early April (or May)
- Finish paper draft soon thereafter
- ???